Global Warming and Hurricanes

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Global warming and skepticism

As a climate scientist, I have devoted 25 years to conducting research on a variety of topics with the goal of addressing uncertainties in the climate system so as to improve our understanding and our ability to simulate and predict the climate system using models. My research has focused on the impact of clouds on the earth's energy balance, the exchange of energy between the ocean and the atmosphere, the influence of aerosols on cloud and radiation characteristics, the thermodynamics of sea ice, and most recently the impact of warming sea surface temperatures on the characteristics of tropical cyclones.

Scientific researchers naturally focus their research on uncertainties, and scientific understanding progresses as new ideas are developed and tested. Skepticism and the competitive clash of ideas move knowledge forward. Constructive skepticism is a mainstay of the scientific method and it has a long and noble tradition in science. The history of my personal skepticism regarding anthropogenic greenhouse warming is described in the following paragraphs.

At the time of Dr. James Hansen's 1988 testimony that global warming was underway, I thought that there were too many uncertainties in both the observational record and the climate models to support such a conclusion. In short, I was skeptical. In the 1990's, my personal research program focused on climate feedbacks in the Arctic. A feedback is the response of nonlinear system (e.g., the coupled climate system) such that a change to the system will be enhanced (positive feedback) or diminished (negative feedback). Based upon observations and climate model simulations available in the early 1990's, climate models were predicting more warming in the Arctic than had been observed. A group of scientists including myself conducted a comprehensive research program in the Arctic Ocean that culminated in a major field expedition 1997-1998, the Surface Heat Budget of the Arctic Ocean (SHEBA; Uttal et al. 2001). SHEBA focused on documenting and understanding feedbacks among the atmosphere, sea ice and ocean towards addressing the discrepancies between observations and climate models. It was hypothesized that there must be negative feedbacks somewhere in the Arctic climate system that were acting to counter the greenhouse warming. However, a principal result of SHEBA was that we identified a number of feedbacks that were more strongly positive than previously believed, that were acting to amplify the greenhouse warming. As a result of SHEBA, and my increasing awareness of the impacts of the warming in the Arctic (see ACIA 2004), I became convinced that greenhouse warming was having a substantial impact in the Arctic. In the last decade, the observed warming in the Arctic has more than caught up with the warming simulated by climate models.

In addition to my own personal research experiences in the Arctic, a series of national and international assessments undertaken by the Intergovernmental Panel on Climate Change (IPCC), the U.S. National Academies, and the U.S. Climate Change Science have made it very difficult to maintain a credible position of scientific skepticism regarding the influence of humans on global warming. The past year has seen striking resolutions to two controversies involving the data record of climate change that support anthropogenic greenhouse warming: the synthesis report on the surface temperature reconstructions over the past two millennia the (NAS, 2006) and the synthesis and assessment report on temperature trends in the lower atmosphere (CCSP, 2006). Further, the draft IPCC 4th Assessment Report presents climate model simulations that are far more sophisticated and accurate than were available in prior assessments, substantially increasing the credibility of such simulations and the associated projections. The cautious conclusions of the large body of scientists contributing to these assessment reports by evaluating a large body of published research are extremely important in providing a balanced overview of the state of knowledge in the scientific research community. Based upon these assessments, our understanding of how the climate system works, while incomplete, is more than sufficiently robust to afford a basis for rational action.

Of the likely impacts of anthropogenic greenhouse warming, the prospect of increased hurricane activity arguably has the greatest near-term socioeconomic impact. Prior to the 2005 North Atlantic hurricane season, Trenberth (2005) published commentary in *Science* raising the issue as to whether the increase in North Atlantic hurricane activity since 1995 could be attributed to global warming. I was skeptical of this idea at the time, since it did not seem reasonable to infer anything about the impact of global warming on hurricane activity merely by examining data in the North Atlantic. Trenberth's paper motivated a group at Georgia Tech (led by Peter Webster) to begin looking at global hurricane data. In August, Emanuel (2005) published a paper in *Nature* associating the increase in sea surface temperature (SST) with an increase in maximum hurricane potential intensity and the destructive capacity of hurricanes, focusing on hurricanes in the North Atlantic and North Pacific. Webster et al. (2005; hereafter WHCC) in an article in *Science* showed that since 1970 the total number of hurricanes has not increased globally, but the proportion of category 4 and 5 hurricanes had doubled, implying that the distribution of hurricane intensity has shifted towards more intense hurricanes.

The following paragraphs summarize the arguments and data that support the link between increased hurricane activity and global warming, including uncertainties in the data and its interpretation.

The data: detection of increased hurricane activity

Central to the argument that global warming is causing increased hurricane activity is analysis of the data. The most reliable data on tropical cyclones (which includes tropical storms and hurricanes) is in the North Atlantic. The HURDAT data prepared by the National Hurricane Center goes back to 1851. Prior to 1944, only surface-based data were available (e.g. landfalling storms and ship observations). Since 1944, aircraft reconnaissance flights have been made in nearly all of the North Atlantic tropical cyclones and hence the record since 1944 is most reliable (Owens and Landsea 2003). Since 1970, satellite observations have made observing and monitoring tropical cyclones even more accurate.

Figure 1 shows the time series in the North Atlantic of the numbers of named storms (tropical cyclones), hurricanes, and category 4 +5 hurricanes (NCAT45; NCAT45 is not shown prior to 1944 owing to concerns about data accuracy). To highlight the decadal and longer-term variability, the data has been smoothed (11 year running mean) to eliminate the year-to-year variability. A nominal 70-year cycle is evident from peaks ca. 1880 and 1950 and minima ca.

1915 and 1985. Also evident is a nominal 20-year cycle, with most pronounced peaks ca. 1934, 1954, and 1974. However, the most striking aspect of the time series is the overall increasing trend since about 1970 and the high level of activity since 1995.

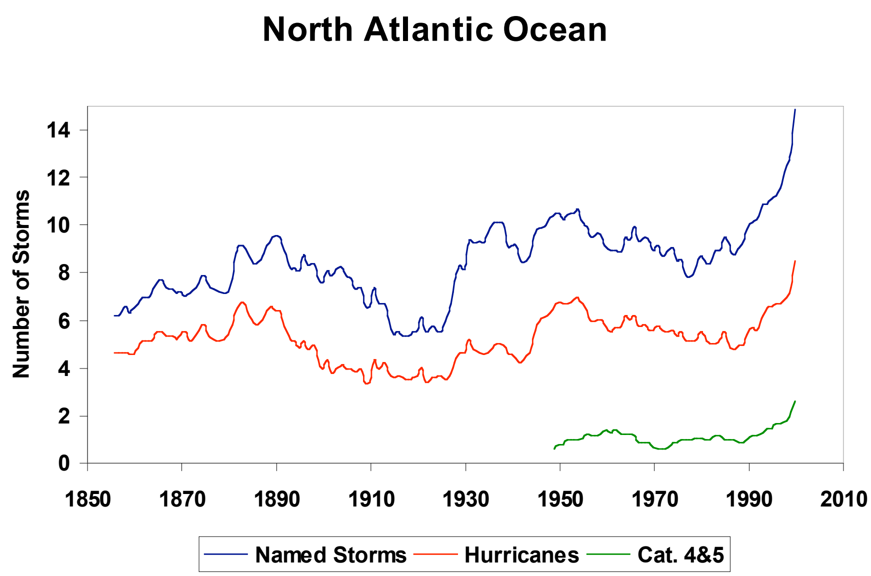

Figure 1: Number of total named storms, hurricanes and category 4-% storms since 1851, filtered by an 11-year running mean. Data are obtained from http://www.aoml.noaa.gov/hrd/hurdat/. Figure courtesy of J. Belanger.

Table 1 compares the statistics for the period 1995-2005 with the previous period of peak activity, 1945-1955. It is seen that current period has 50% more named storms, 50% more hurricanes, and 50% more category 4 +5 storms than the period ca. 1950. It is clear that the current period is not analogous to 1950's and 1960's, since we are just entering the active phase and already the level of activity is 50% greater than the activity in the previous period ca. 1950.

Table 1: Comparison of North Atlantic hurricane statistics for the periods 1945-1955 and 1995-2005 (data from http://www.aoml.noaa.gov/hrd/hurdat/). Curry et al. (2006)

	1945-1955	1995-2005
#Named storms	115	165
# Hurricanes	74	112
# Category 4+5	19	28

One key to understanding why we are seeing more tropical cyclones is to examine the length of the hurricane season (period between the first and last storm of the hurricane season). The official North Atlantic hurricane season is between June 1 and November 30. During the 2005 season, there were two tropical storms in December and January. Figure 2 shows the length of the hurricane season in the North Atlantic since 1851. Evidence of the 70-year and particularly the 20-year cycles is clearly seen. But the most striking aspect of the time series is the trend of increasing season length over the past century, averaging 4.8 days per decade or nearly 50 days over the past century. Most of this lengthening is occurring on the later end of the season.

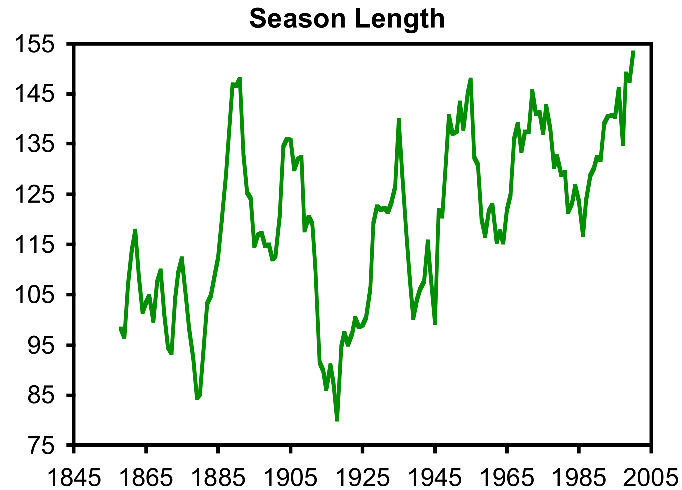

Figure 2: Length (in days) of the North Atlantic tropical cyclone season, filtered by an 11 year running mean. (data from http://www.aoml.noaa.gov/hrd/hurdat/). Figure courtesy of J. Gulledge.

While the data since 1944 are generally agreed to be reliable, what about the quality of data earlier in the record? Figure 3 shows the time series of total named storms and the average sea surface temperature (SST) in the main development region of the North Atlantic. Comparison of the two time series shows coherent variations of the number of storms and the SST for periods greater than 20 years. In particular, the period 1910-1920 with low storm activity is associated with anomalously cool sea surface temperatures. The coherence between the total number of tropical storms and the sea surface temperature on multidecadal time scales lends credence to the tropical storm data in the earlier part of the period, although the storm intensity in the earlier part of the record is arguably much less accurate.

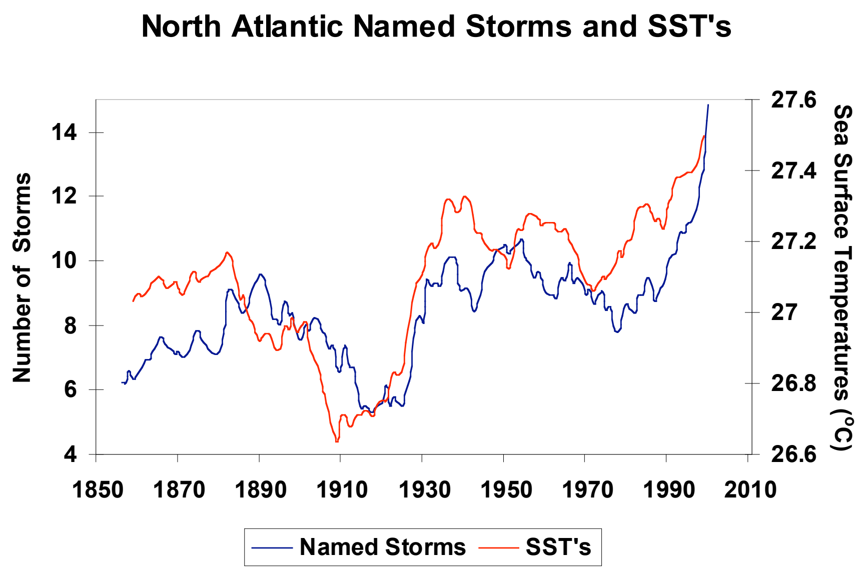

Figure 3: Number of total named storms in the North Atlantic and the average sea surface temperature in the main development region, filtered by an 11-year running mean. Data are obtained from http://www.aoml.noaa.gov/hrd/hurdat/. Figure courtesy of J. Belanger.

The most reliable data set in the early part of the record is the count of the number of storms that have made U.S. landfall (Figure 4). Strong evidence of the 20- and particularly the 70-year cycles are seen in these plots. Again, the activity during the past decade, particularly in terms of the total number of tropical storms, has surpassed the previous peak period in the 1930's – 1950's.

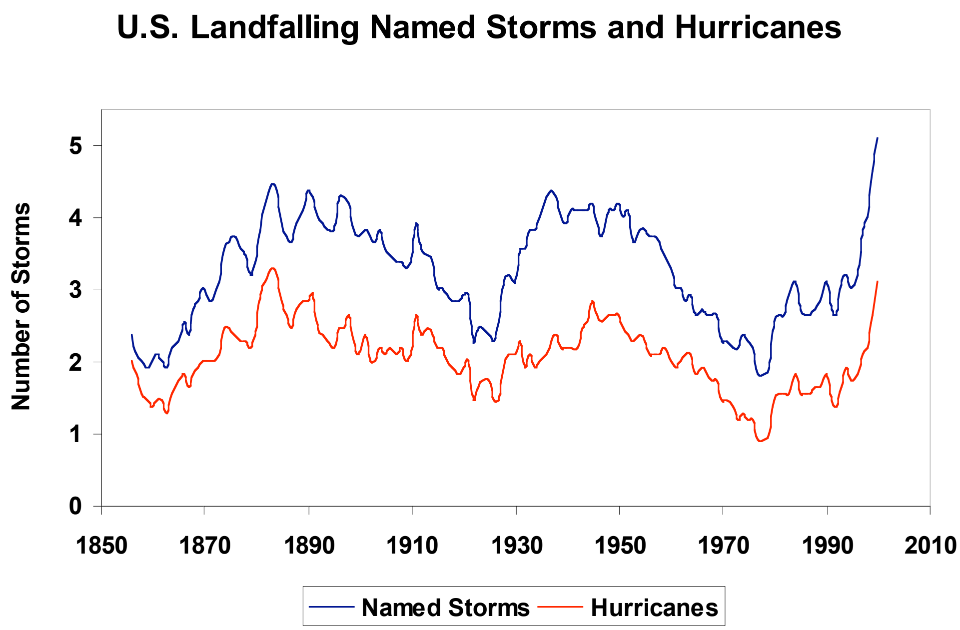

Figure 4: Number of total named tropical storms and hurricanes that have made U.S. landfall, filtered by an 11-year running mean. Data are obtained from http://www.aoml.noaa.gov/hrd/hurdat/. Figure courtesy of J. Belanger

While the data provides strong support for elevated hurricane activity in the North Atlantic that is significantly beyond what has been seen in the historical record, is there evidence of elevated hurricane activity in the other oceanic regions where hurricanes form? Webster et al. (2005) examined the global hurricane activity since 1970 (the advent of reliable satellite data). The most striking finding from this study is that while the total number of hurricanes has not increased globally, the number and percentage of category 4 + 5 hurricanes has nearly doubled since 1970 (Figure 5). While multidecadal oscillations are seen prominently each of the ocean basins, a clear trend in increasing number of NCAT45 hurricanes is seen in each region.

Skeptics have found our analysis unconvincing owing to suspected problems with the data. However, given the existing database and the lack of any rigorous uncertainty analysis of the data, the existing data cannot be used to reject our assertion that the number of category 4 and 5 hurricanes has increased substantially since 1970. There is an obvious need for an improved climate data record for global hurricane characteristics. Efforts are underway at the National Climatic Data Center and the University of Wisconsin to reprocess the satellite data, although it will be a considerable challenge to assemble the data prior to 1977. A consistent method of determining surface wind speed, combined with careful assessment of the satellite data integrity and sampling errors, are essential elements of a reanalysis.

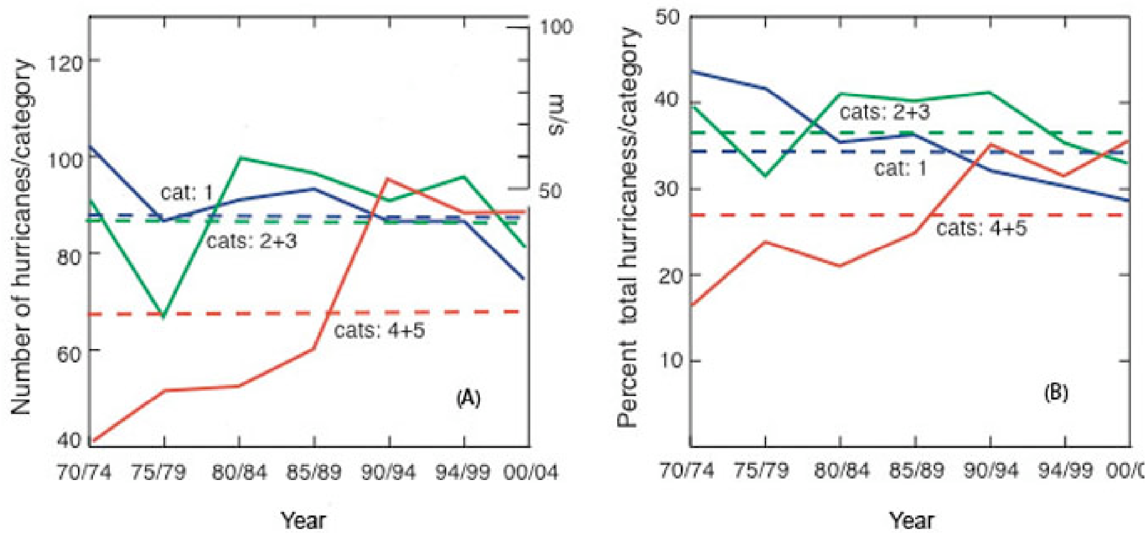

Figure 5: Intensity of global hurricanes according to the Saffir-Simpson scale (categories 1 to 5), in 5 year periods. (**A**) The total number of storms and (B) the percent of the total number of hurricanes in each category class. Webster et al. (2006).

Cause and attribution of the increased hurricane activity

The increase in global hurricane intensity since 1970 and the increase in the number of named storms in the North Atlantic since 1995 are associated directly with a global increase in tropical sea surface temperature (Emanuel 2005; Webster et al. 2005; Hoyos et al. 2006; Elsner et al. 2006). Figure 6 shows the variation of tropical sea surface temperature (SST) in each of the ocean regions where tropical cyclone storms form. It is seen that in each of these regions that the sea surface temperature has increased by approximately 0.5°C (or 1°F) since 1970. The causal link between SST and hurricane intensity was established over 50 years ago, when it was observed that tropical cyclones do not form unless the underlying SST exceeds 26.5°C and that warm sea surface temperatures are needed to supply the energy to support development of hurricane winds (e.g., Gray, 1968). The role of SST in determining hurricane intensity is generally understood and is supported by case studies of individual storms and by the theory of potential intensity (e.g. Emanuel 1987). Hoyos et al. (2006) have clarified the relationship between seasonally-averaged hurricane intensity and the seasonally-averaged tropical SST in individual ocean basins. By isolating the trend from the shorter modes of variability and applying a methodology based on information theory, Hoyos et al. found that the global increase in category 4 and 5 hurricanes for the period 1970-2004 is directly linked to the trends in SST.

Skeptics have argued that wind shear plays a predominant role in variations of hurricane intensity (e.g. Klotzbach 2006; Chan 2006). While the intensity of an individual storm may be determined by wind shear and even the intensity of storms in an entire season may be dominated by wind shear (e.g. in an El Nino year), there is no trend in wind shear since 1970 that can explain the global increase in hurricane intensity (Figure 7).

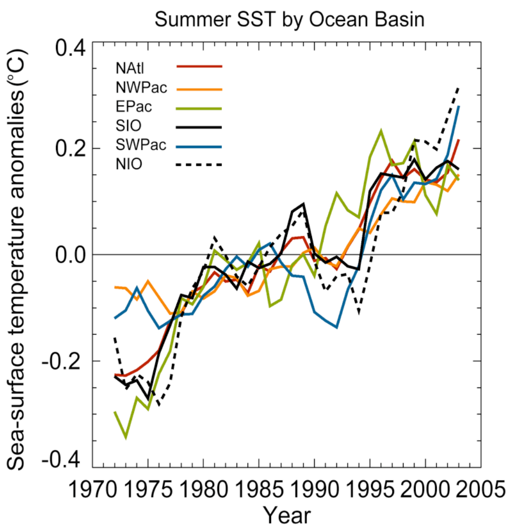

Figure 6. Evolution of the sea surface temperature anomalies relative to the 1970-2004 period for the North Atlantic, Western Pacific, East Pacific, South Indian Ocean, Southwest Pacific and North Indian Ocean Basins (Curry et al., 2006).

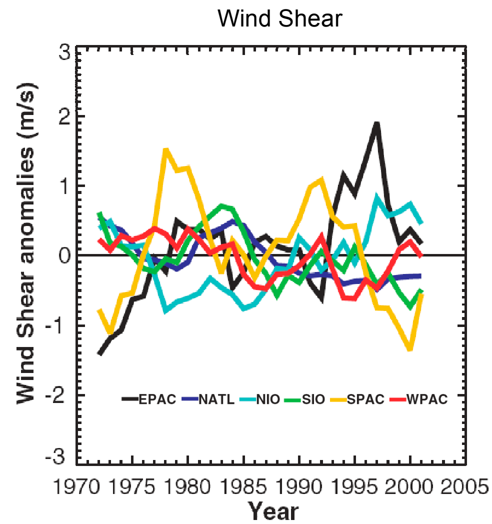

Figure 7. Evolution of the wind shear anomalies relative to the 1970-2004 period for the North Atlantic, Western Pacific, East Pacific, South Indian Ocean, Southwest Pacific and North Indian Ocean Basins (Hoyos et al., 2006).

A number of natural internal oscillations of the atmosphere/ocean system have a large impact on SST (e.g. El Nino, North Atlantic Oscillation). However, decadal-scale oscillations tend to be specific to each ocean basin and are often anti-correlated from one basin to another. The data show that the tropical SST increase is global in nature and occurs consistently in each of the ocean basins (Figure 6). This tropical warming is consistent with a similar increase in global surface temperatures (Figure 8). External forcing factors, such as volcanic eruptions and solar

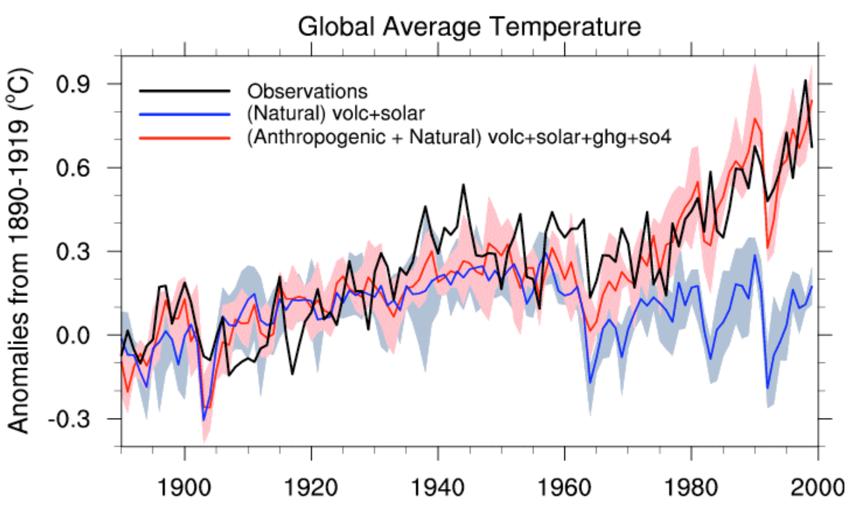

Figure 8. The four-member ensemble mean (red line) and ensemble member range (pink shading) for globally averaged surface air temperature anomalies for all forcing (volcano + solar + GHG + sulfate + ozone); the solid blue line is the ensemble mean and the light blue shading is the ensemble range for globally averaged temperature response to natural forcing (volcano + solar); the black line is the observations after Folland et al. (2001). Taken from Meehl et al. 2004.

variability, which are also natural causes, are known to produce global responses in surface temperature. The surface temperature trends over the last century has been extensively studied as summarized in the IPCC TAR (2001) and detailed in subsequent climate modeling studies (Figure 7; Meehl et al. 2004). The unanimous conclusion of these climate model simulations is that the global surface temperature trend since (including the trend in tropical SSTs) cannot be reproduced in climate models without inclusion of anthropogenic greenhouse gases. Knutson et al. (2006) specifically attributed the increase in global tropical sea surface temperatures to greenhouse warming.

In summary, the arguments for the hypothesis that

Greenhouse warming is causing an increase in global hurricane intensity

have been presented as a causal chain:

1. *Frequency of the most intense hurricanes is increasing globally.*
2. *Average hurricane intensity increases with increasing tropical SST.*
3. *Global tropical SST is increasing as a result of greenhouse warming*

Skeptics argue that the increase in hurricane intensity reported by Emanuel (2005) and Webster et al. (2006) is greater than that expected from the theory of potential intensity and from climate model simulations (Knutson and Tuleya, 2004; Oouchi et al. 2006), by a factor of 2-4. Skeptics have used this inconsistency in two ways: first, to argue that the observed trend cannot be associated with greenhouse warming, because it does not agree with the model and theoretical results (Landsea, 2005); and second, to argue the model results are wrong, because they are not supported by the observations (Michaels et al, 2005). The appropriate way to interpret the finding that the model simulations show a slower increase of hurricane intensity than do the data is that the models may be underestimating the impact of global warming on hurricane intensity or there are additional mechanisms whereby SST indirectly influences hurricane intensity in ways that are not accounted for by theories of potential intensity or the climate models. Michaels et al. (2006) argue for a step-like, rather than continuous, influence of SST on tropical cyclone intensification.

Skeptics have argued that the causal chain linking hurricane intensity to an increase in tropical sea surface temperature caused by greenhouse warming should also hold for individual ocean basins (e.g. Chan 2006), and I concur with this. The North Atlantic hurricanes deserve special discussion in light of the relatively long historical record of hurricanes, and the repeated assertions from the National Hurricane Center that the recent elevated hurricane activity is associated with natural variability, particularly the Atlantic Multidecadal Oscillation (AMO). Figures 1-4 suggest that natural modes of multidecadal variability, notably the AMO (~70 year cycle), do have an influence on North Atlantic hurricane activity. However, recent examination of the data by Mann and Emanuel (2006) and Trenberth and Shea (2006) suggest that the impact of the AMO on tropical sea surface temperature and hurricane activity has been overestimated owing to the convolution of the AMO with the global forcing (natural plus anthropogenic). Analyses that rely solely on SST to identify the AMO may have aliased the phase and amplitude of the AMO signal (Mann and Emanuel, 2006). The observations of Bryden et al. (2005) show that the North Atlantic thermohaline circulation has decreased during the period since 1950, suggesting that there is no rationale for supposing that the AMO has moved into an anomalously positive phase. And most compellingly, the strength of the tropical storm activity during the period 1995-2005 (which is at least a decade away from the expected peak of the current AMO cycle), is already 50% greater than the previous peak period ca. 1950 (Table 1).

What can we conclude from the above analysis? The evidence that greenhouse warming has caused an increase in tropical sea surface temperature is substantial. The link between sea surface temperature and hurricane intensity is well understood theoretically and is supported observationally. The causal chain linking the increase in global hurricane intensity to global warming cannot be invalidated by the available evidence. The primary issue is whether the magnitude of the observed increase in hurricane intensity is as large as that found by Webster et al. (2005), given concerns about the quality of the data. As previously stated, a reanalysis of the global hurricane data set is needed to create a robust and homogeneous climate data record. Current efforts to use very high resolution coupled climate models to examine the impact of global warming on hurricane characteristics will also shed new light on the subject once these models are capable of simulating realistic tropical cyclones.

While both groups of scientists (those that support the natural variability explanation and those that support the global warming contribution) agree that hurricane activity in the North Atlantic will remain elevated for some years, the implications for future projections of hurricane activity are quite different. Based upon the hypothesis of natural variability being the cause of the high hurricane activity in the North Atlantic since 1995, there have been several predictions of a forthcoming downturn in hurricane activity: Goldenberg et al. (2001) imply a downturn in 10-40 years; and Gray (2006) anticipates a downturn in 3-8 years associated with a global cooling. By contrast, based upon the historical data record in the North Atlantic, an increase of 0.5°C (1°F) in tropical sea surface temperature implies an additional 5 tropical storms per season (Figure 9), and hence global warming will result in an continued increase in the number of North Atlantic storms and hurricane intensity globally.

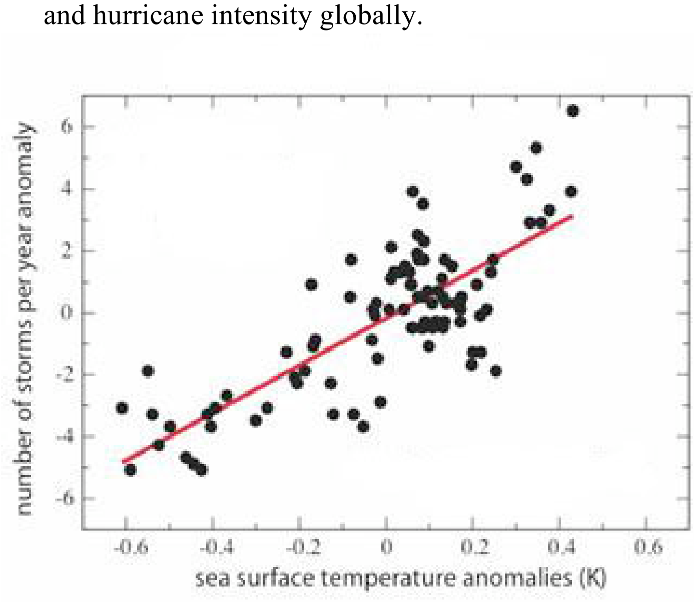

Figure 9: Relationship between the total number of North Atlantic tropical storms and hurricanes and the sea surface temperature, using data points that are 5-year running averages for the period 1910-2005. Figure courtesy of J. Gulledge.

It may take up to a decade for the observations to clarify the situation as to which explanation, natural variability or global warming, has better predictive ability. In the short term, evaluation of seasonal forecasts for the North Atlantic can provide some insights into the predictive capability of natural variability. Holland (2006) has conducted an assessment of statistical forecasts of North Atlantic tropical storm activity. Seasonal forecasts are based upon the statistics of North Atlantic tropical storms for the period since 1950. W. Gray commenced making seasonal forecasts in 1984. For the first decade (until 1994), Gray's forecasts performed well (Figure 10), with a bias error of -0.2 storms per season for the June forecasts and a root mean square error of 1.8. In the period since 1998, Gray's forecasts have performed much worse, with a notable low bias averaging -3.1 storms per season and a root mean square error of 5.2. NOAA's seasonal forecasts for the same period show little variation from Gray's forecasts. It is argued here that the persistent low bias in the seasonal forecasts since 1995 indicates that the elevated activity in this period cannot be explained solely by natural variability seen in the historical data record since 1950.

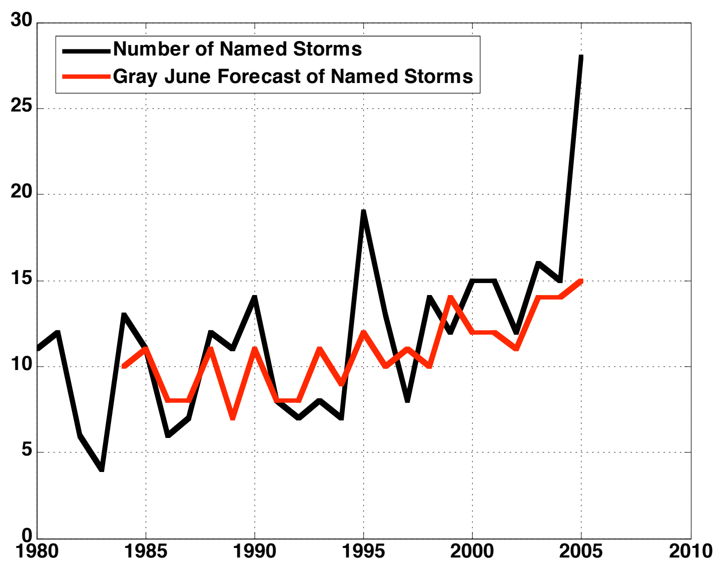

Figure 10: Evaluation of W. Gray's seasonal June forecasts for North Atlantic named storms. Figure courtesy of G. Holland.

Finally, I return to the general issue of skepticism about hurricanes and global warming. Skepticism about whether the global warming argument has been made convincingly is not the same as assuming that the converse (natural variability) must therefore be true. The arguments for natural variability are refuted by: the known range of natural variability in the existing database; and the absence of a convincing mechanism for natural variability that can explain the global increase in both oceanic temperatures and the frequency of intense hurricanes.

Mixing politics and science

Mixing politics and science is unavoidable on scientific topics of significant societal and policy relevance. However, this process, aided and abetted by the media, often politicizes the science and polarizes the scientific community in ways that are detrimental both to the scientific and policy processes. While the scientific debate on the topic of hurricanes and global warming has been proceeding in the peer reviewed scientific journals (as summarized above), the public debate in the media and even in congressional testimony has unfortunately diverged from the scientific debate. As the scientific debate continues and uncertainties in this research are addressed, one would hope that the general message conveyed to the public and to policy makers is that a scientific debate is underway by respected research scientists on the subject of a link between global warming and hurricanes and that the research findings, if correct, imply an elevated risk for increased damage from future hurricanes as global warming proceeds. Instead, there have been substantial public efforts to ignore and/or discredit this research and even the scientists that have been conducting this research. This divergence of the public debate from the scientific debate has confused and misled the public and policy makers on this important issue.

After considerable reflection motivated by my personal experiences this past year with the media, the public, and policy makers as a result of publication of the Webster et al. paper, I have come to the following understanding of the complex interplay of issues that have contributed to this situation:

- The influence of global warming deniers, consisting of a small group of scientists plus others that are motivated to deny global warming owing to the implications associated with any policy to control greenhouse gas emissions
- The tendency of a large number of forecast meteorologists (including TV meteorologists) to deny global warming and in particular the possibility of a link between increasing hurricane intensity and global warming
- The public statements by NOAA administrators and National Weather Service scientists that neglect the published research and deny a link between hurricanes and global warming
- The role of certain elements of the media in promoting divisiveness among the scientists, polarizing the debate, and legitimizing disinformation

The issue that is arguably of greatest concern to research scientists is the public position taken by NOAA on the issue of hurricanes and global warming. Statements by NOAA administrators and selected scientists from the National Weather Service in Congressional testimony, press communications, and website material have categorically denied a connection between global warming and increased hurricane intensity. Most egregiously, on its web site http://www.magazine.noaa.gov/stories/mag184.htm NOAA states that there is a consensus of NOAA scientists on this issue, although public identification of a number of NOAA scientists that did not agree with this consensus opinion resulted in an addendum at the end of the online article to state that the agreement is among *some* NOAA researchers and forecasters. This information being disseminated by NOAA is misleading, incomplete and one-sided, and does not accurately reflect the state of knowledge as reflected in the published scientific literature. NOAA's statements, by default, are viewed by the public as the official federal position on hurricanes and global warming. Government leadership that is willing and able to engage in an appropriate representation of scientific research is essential for scientifically well-informed national planning and preparedness.

The adverse impacts of misleading information on the hurricanes and global warming issue were emphasized to me during a recent lecture tour through Florida. In our meeting with Governor Jeb

Bush on 31 May, Governor Bush voiced frustration over the disagreement between the National Hurricane Center and climate researchers and also the media furor that made it very difficult to assess the actual risk. Florida is extremely vulnerable to any increase in hurricane activity. During the past 10 years 48% of U.S. landfalling hurricanes have struck Florida, and during 2004 it has been estimated that 1 in 5 Florida homes were damaged by hurricanes striking Florida that year.

Given the important socioeconomic impacts and policy implications, the scientific controversies, and the divergence of the public from the scientific debate, an independent scientific assessment is needed on the topic of hurricanes and global warming. I hope that such an assessment would clarify the scientific debate, identify the uncertainties, and illuminate the fuzzy thinking that has entered into the public debate. The National Research Council Board on Atmospheric Science and the Climate Research Committee have prepared a proposal for such an assessment study, but the NRC has thus far been unable to identify funding for this study (Chris Elfring, NAS, personal communication).

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